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MAGNETOSPHERIC PLASMA WAVE RESEARCH 1975-1978

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Introduction

In this review the term "plasma wave" is used to denote all waves which are generated in the magnetospheric plasma or which have their wave characteristics significantly modified on propagation through the magnetosphere. These plasma waves are both electromagnetic and electrostatic and are generally generated by the conversion of free energy within the plasma into wave energy through a variety of plasma-wave processes. Plasma waves may in turn interact with plasma particles locally or at remote locations in the magnetosphere to modify the particle populations leading to such phenomena as particle precipitation.

Plasma wave research has led to the identification of numerous plasma wave phenomena within the terrestrial magnetosphere. Many of these plasma wave types are associated with the different regions of the magnetosphere as depicted in Figure 1. A listing of the location of these plasma wave types along with the observed frequency range and a description of the wave properties is given in Table 1. Within the magnetosphere, detected plasma waves range in frequency from millihertz--well below the ion gyrofrequency at the bow shock--to 10 megahertz--approximately the electron plasma frequency in the ionosphere. Within the Jovian magnetosphere plasma wave phenomena extend up to 40 MHz which is the maximum electron gyrofrequency in the Jovian ionosphere.

A review of magnetospheric wave phenomena during the previous quadrennium has been given by Barfield [1975]. Significant research during that period concentrated on the role of the plasmapause in magnetic pulsation generation and propagation; the role of ion cyclotron waves in plasmaspheric wave-particle interactions; the discovery of $(n + \frac{1}{2})$ electron cyclotron harmonic radiation and of plasmaspheric hiss; and the analysis of storm time Pc 5 waves. Within the present quadrennial period, 1975-1978, a number of volumes have been published which include reviews of terrestrial and Jovian magnetospheric wave research and of associated plasma and energetic particle phenomena [Knott and Battrick, 1975; Hultqvist and Stenflo, 1975; Formisano, 1975; Williams, 1976; McCormac, 1976; Gehrels, 1976, Kennel, Lanzerotti and Parker, 1978]. Specific review papers covering a wide variety of plasma wave topics include, for example, Barnes [1978], on waves in the solar wind; Orr [1975], Lanzerotti [1976], Coleman and McPherron [1976], Wertz and Campbell [1976], and Rostoker [1979], on hydromagnetic waves and magnetic pulsations; Papadopoulos [1977] and Farley [1978] on ionospheric wave phenomena; Kennel [1975], Fredricks [1975a, b], Lyons [1976a, 1978], Scarf [1975a], Scarf and Russell [1976b], and Thorne [1975, 1976], on wave-particle interactions; D'Angelo [1977] on plasma waves and instabilities in the polar cusp; Gurnett [1976a] on electrostatic turbulence in the magnetosphere; Gurnett [1976b] on plasma waves escaping the magnetosphere; Walker [1976] on the theory of whistler propagation; Booker [1975a, b] on radio propagation and whistlers; Benson [1977] on stimulated plasma waves in the ionosphere; and Helliwell and Katsufrakis [1978] on controlled wave-particle experiments. Plasma wave phenomena occurring in the Jovian Magnetosphere are

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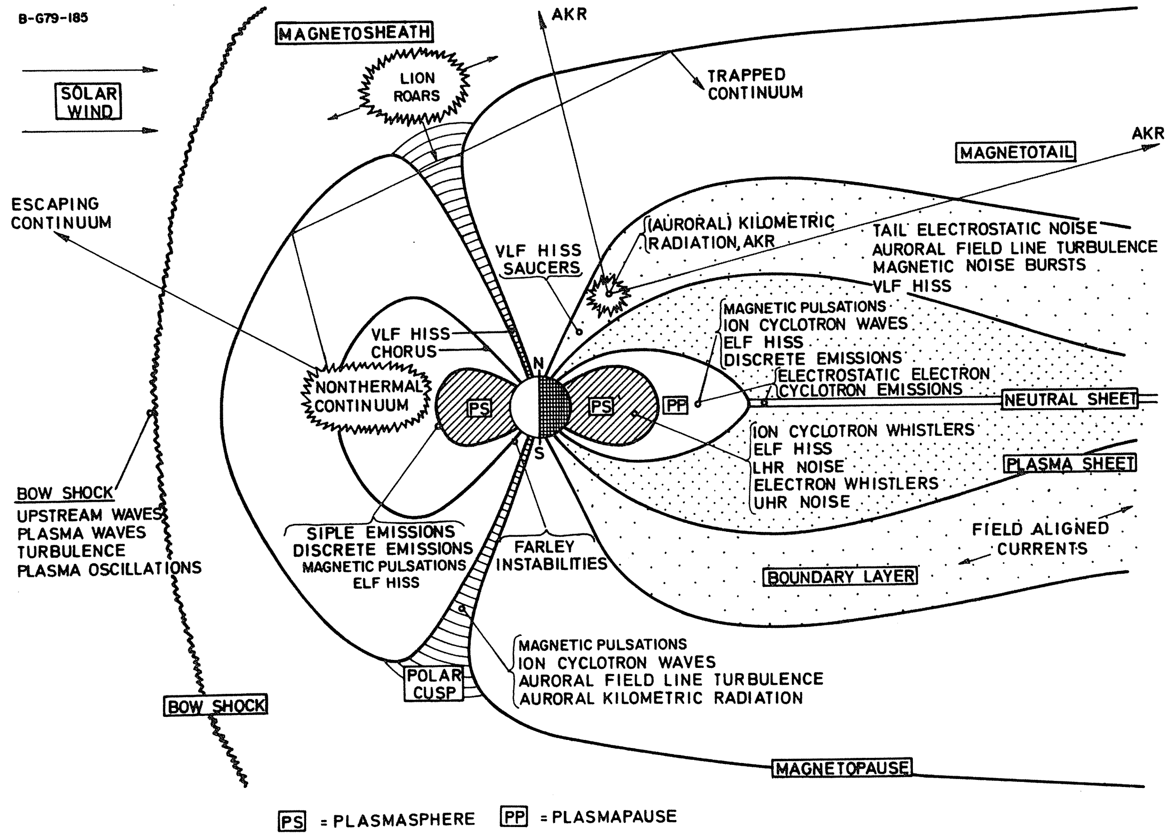

Figure 1. Types of magnetospheric plasma waves and regions of occurrence in a noon-midnight meridian cross-section of the Earth's magnetosphere [from Shawhan, 1978].

receiving more attention because of the successful Pioneer 10 and 11 measurements and the pending Voyager-1 and 2 encounters. A review of decametric and hectometric emissions is given by Carr and Desch [1975] and models for this radiation by Smith [1975]. Scarf [1975b] predicts the nature of wave-particle interactions based on terrestrial phenomena. Shawhan [1978], in a report prepared for the U. S. National Academy of Sciences, Space Science Board, summarized the progress of magnetospheric plasma wave research through 1976 and gives a position on the direction of this field of research.

This review concentrates primarily on research contributions of U.S. investigators during the 1975-1978 quadrennium in the area of magnetospheric plasma waves within the magnetospheres of the Earth and Jupiter. Plasma wave phenomena in the solar wind are reviewed in this volume by the Review and Quadrennial Report on "Physics of the Solar Wind" [Barnes, 1979], and on "Interplanetary Type III Radio Bursts" [Papadopoulos, 1979]. Related Quadrennial Reports in this volume which include plasma wave phenomena are "The Electric Fields and Global Electrodynamics of the Magnetosphere" [Stern, 1979], "Dynamics of the Jovian Magnetosphere" [Goertz and Thomsen, 1979] and "Magnetospheric Substorms" [McPherron, 1979]. Not included in this review are the topics of incoherent backscatter radar, ionospheric heating experiments, and plasma sounders although some representative papers are included in the bibliography.

Some of the more significant research accomplishments during this four year period include:

-- measurement of the electromagnetic and electrostatic power spectra of noise in the bow shock and magnetosheath region.
-- discovery of both magnetic noise bursts and broadband electrostatic noise in the magnetotail.
-- characterization of instability produced MHD and ion cyclotron waves in the polar cusp region.
-- theoretical interpretation of the $(n + \frac{1}{2})$ electron cyclotron harmonic noise bands outside of the plasmapause.
-- characterization of the intense kilometric radiation from the auroral regions which marks the Earth as a 10^9 watt emitter in analogy to the Jovian decametric emissions.
-- association of electrostatic ion cyclotron turbulence, VLF hiss, and kilometric radiation on auroral field lines with the auroral particle acceleration process.
-- identification of VLF emissions possibly stimulated by harmonics of the world's power lines.
-- intensive diagnostics of whistler mode wave propagation and interaction with energetic particles through active VLF transmitter experiments.

Plasma Wave Instrumentation

Several new plasma wave phenomena have been discovered and other phenomena more definitively characterized because of measurements provided

Table 1. Plasma Wave Phenomena and Characteristics*

Phenomenon	Location	Observed Frequency	Wave Properties
Geomagnetic Pulsations and Magnetohydrodynamic Waves	Polar Cusp Plasmapause	0.001 Hz - 10 Hz	Transverse and compressional Alfvén waves transmitted along geomagnetic field lines. Excited at time of geomagnetic storms on nightside. Excited by Kelvin-Helmholtz instability at quiet times on dayside. Indicators of changes in magnetosphere configuration.
Ion Cyclotron Waves	Plasmapause Polar Cusp	0.5 Hz - 100 Hz	Spectrum of waves just below the ion cyclotron frequency. Generally L.H. polarized. Causes proton precipitation?
Bow Shock Plasma Waves	Bow Shock Magnetosheath	20 Hz - 200 Hz	Electromagnetic turbulence comprised of bursts of whistler mode waves.
Lion Roars	Magnetosheath	90 Hz - 160 Hz	Packets of whistler-mode waves propagating along magnetic field. Associated with magnetic storms.
Magnetic Noise Bursts	Auroral Field Lines Neutral Sheet	10 Hz - 600 Hz Peak ~ 100 Hz	Superposition of intense bursts of magnetic noise. Associated with tail electrostatic noise and similar to lion roars.
Ion Cyclotron Whistlers	Ionosphere Plasmasphere	10 Hz - 750 Hz	L.H. polarized tones rising to the ion cyclotron frequency. Provides information on ion densities and temperatures.
ELF Hiss (Plasmaspheric)	Plasmapause Plasmasphere Detached Plasma Regions	10 Hz - 5 kHz	Whistler-mode turbulence at all local times. Fills plasmasphere. Causes electron precipitation from outer radiation zone.
Chorus	Outside Plasmasphere	10 Hz - 5 kHz	Series of overlapping rising or falling tones. Quasi-periodic. Predominantly dayside equator.
VLF Hiss (Auroral and V-Shaped)	Auroral Field Lines	10 Hz - 100 kHz	V-shaped noise bands in frequency-time, often superimposed. Downgoing waves < 2500 km. Associated with electrostatic turbulence.
Saucers	Auroral Field Lines	500 Hz - 30 kHz	V-shaped noise bands in frequency-time, often superimposed. Upgoing waves > 1000 km.
Discrete Emissions	Plasmapause	1 kHz - 12 kHz	Rising, falling, or mixed tones, sporadic or quasi-periodic. Rarely seen with spacecraft.
LHR Noise	Auroral Zone Plasmapause	4 kHz - 18 kHz	Intense noise band above LHR frequency, nearly electrostatic with $\hat{k} \perp \hat{B}_o$.

*Adapted from Shawhan [1978]

Phenomenon	Location	Observed Frequency	Wave Properties
Upstream Whistler Mode Waves	Upstream of Bow Shock in Solar Wind	0.01 Hz - 4 Hz 20 kHz - 70 kHz	Two bands; below ion cyclotron and below electron cyclotron frequency.
Trapped Non-Thermal Continuum Radiation	Outside Plasmapause Inside Magnetosheath	500 Hz - 20 kHz	Weak broadband noise trapped between plasmapause and magnetosheath. Generated on dayside 0400 - 1400 LT.
UHR Noise	Plasmapause	100 - 600 kHz	Intense noise band near upper hybrid resonance frequency.
Electron Whistlers	Plasmasphere Plasmapause	100 Hz - 1 MHz	R.H. polarized falling tones. Travel along magnetic field lines in ionization ducts or can be refracted across field lines.
Tail Broadband Electrostatic Noise	Magnetotail at Boundaries of Plasma Sheet	10 Hz - 2 kHz	Broadband emission consisting of discrete bursts with V-shaped structure, $\hat{k} \perp \hat{B}_o$. Associated with VLF hiss in same region and with AKR.
Auroral Field Line Turbulence	Auroral Field Lines All Local Times	10 Hz - 10 kHz Peak 10 - 50 Hz	Broadband emission consisting of discrete bursts at V-shaped structure. Associated with VLF hiss in same region with AKR.
Farley Instabilities	Ionosphere E-Region	40 Hz - 10 kHz	Narrowband ELF emission at $\sim$ 100 Hz. Broadband VLF emission $<$ 10 kHz at higher altitude.
Electrostatic Electron Cyclotron Emissions	Outside Plasmapause; Near Plasma Sheet	200 Hz - 50 kHz	Narrowband emission near $(n + \frac{1}{2})\, f_g^-$ with several harmonics observed simultaneously.
Bow Shock Turbulence	Bow Shock Transition Magnetosheath	200 Hz - 30 kHz	Broadband electrostatic noise.
Bow Shock Plasma Oscillations	Bow Shock	3 kHz - 50 kHz	Narrowband electron plasma oscillations associated with electron heating.
Escaping Non-Thermal Continuum Radiation	Outside Plasmapause Magnetosphere	20 kHz - 100 kHz	Weak electromagnetic broadband noise escaping magnetosphere. Generated in morning and early afternoon. Associated with bands of electrostatic cyclotron noise at plasmapause.
Kilometric Radiation (Auroral or Terrestrial) (AKR or TKR)	Auroral Field Lines	20 kHz - 2 MHz	Broadband noise bursts peaked $\sim$ 200 kHz beamed into 2 sterad cone centered on auroral field lines at $\sim 2\, R_E$ emitting $\sim 10^9$ W. Associated with VLF hiss, ELF hiss, auroral turbulence, and tail electrostatic noise. Generated $\sim$ 2200 LT in tail and $\sim$ 1200 LT in cusp.

Phenomenon	Location	Observed Frequency	Wave Properties
Power System Harmonic Radiation	Plasmasphere Boundary $L \sim 4$	kHz	Narrowband radiation at harmonics of the rectified 60 Hz, spaced by 120 Hz and falling in kHz range. Affects other emissions at close frequencies.
Siple Stimulated VLF Emission	Plasmasphere Boundary $L \sim 3\text{-}5$	2 kHz - 16 kHz	Narrowband emissions, rising or falling tones, stimulated and modified by transmitted VLF waves.
Electron Beam Stimulated Emissions	Ionosphere	DC - 12 MHz	Waves stimulated by rocket-borne electron and argon guns: f_p^-, $2f_g^-$ and VLF and ELF whistler mode frequencies.

f_g^- = electron gyrofrequency

f_p^- = electron plasma frequency

LHR = lower hybrid resonance frequency (LHR)

UHR = upper hybrid resonance frequency (UHR)

L.H. and R.H.
= left- and right-hand polarization

$\hat{k}$ = wave normal vector direction

$\hat{B}_o$ = geomagnetic field direction by plasma wave instrumentation carried by U. S. satellites within the 1975-1978 time frame. Spacecraft active in the magnetosphere within this period include IMP-6, -7, -8, ATS-6, Hawkeye-1, RAE-2, Voyager-1 and -2, S3-3, and ISEE-1 and -2. This combination of spacecraft has carried plasma wave instruments throughout the magnetosphere to 46 R_E, through the polar cusp and along field lines.

Many of these plasma wave instruments contain both magnetic and electric field sensors so that electromagnetic waves can be distinguished from electrostatic phenomena. The frequency range covered by the combined responses of magnetometers, plasma wave receivers, and radio astronomy receivers span the plasma wave range of interest--millihertz to megahertz. Some descriptions of representative plasma wave instrumentation are included in the following papers: IMP-6 and -8 and Hawkeye-1 [Kurth et al., 1975; Green et al., 1977]; ATS-6 [McPherron et al., 1975]; RAE-2 [Kaiser and Alexander, 1976]; S3-3 [Mozer et al., 1977]; Voyager-1 and -2 [Scarf and Gurnett, 1977; Warwick et al., 1977]; and ISEE-1 and -2 [Gurnett et al., 1978]. In addition ground-based VLF transmitters have been providing controlled waves with which to examine wave-particle processes. The Siple transmitter is described by Helliwell and Katsufrakis [1978] and a transportable VLF transmitter (TVLF) by Koons [1975].

Bow Shock and Magnetosheath

Bow Shock Whistler Mode and Electrostatic Waves

Thorough reviews of upstream whistler mode waves and of whistler mode and electrostatic turbulence in the bow shock and magnetosheath regions are given by Fredricks [1975a, b] and by Fairfield [1976a, b]. A model for the generation of waves upstream from the bow shock due to reflected protons was proposed by Fredricks [1975c]. Rodriguez and Gurnett [1975, 1976] determined the spectral characteristics of bow shock and magnetosheath wave noise for the first time. They found electrostatic turbulence in the range of 200 Hz to 4 kHz and found it to correlate with the electron to proton solar wind temperature ratio. The electromagnetic turbulence covered a frequency range of 20 Hz to 4 kHz and was related to the upstream solar wind electron density for shock angles of ~ 90°. Electromagnetic wave phenomena were also detected at the dawn and dusk magnetosphere boundaries with IMP-7 [Scarf et al., 1977].

Magnetosheath "Lion Roars"

Smith and Tsurutani [1976] report on an electromagnetic phenomena which they call "lion roars". These electromagnetic wave packets of ~ 2 second duration at ~ 120 Hz have an amplitude of ~ 85 milligamma and seem to be correlated with the level of geomagnetic activity. This same phenomena is reported by Gurnett and Frank [1977] using Hawkeye-1 data.

Non-thermal Continuum Radiation

A weak, broadband radiation apparently associated with energetic electrons in the outer radiation zone has been reported by Gurnett [1975, 1976b]. This non-thermal continuum radiation is found in a range of 500 Hz - 100 kHz. Below the solar wind plasma frequency (~ 30 kHz) this noise is trapped within the magnetosheath regions between the magnetopause and the plasmapause; for higher frequencies the noise can escape the magnetosphere. This noise might be analogous to the Jovian decametric radiation or might result from coupling to electromagnetic waves from regions of intense electrostatic waves [Gurnett, 1975, 1976b].

Magnetotail and Plasma Sheet

The excursion of IMP-8 to 46 R_E in the distant magnetotail and plasma sheet has provided the first identification of the plasma wave types existing in this region [Gurnett et al., 1976]. Broadband electrostatic noise is observed. This noise is found in the frequency range of 10 Hz to several kHz and is both intense and frequent and seems to be associated with streaming keV protons. Less frequently observed magnetic noise bursts are nearly monochromatic with durations of seconds. This noise seems to be similar to "lion roars" observed in the magnetosheath [Smith and Tsurutani, 1976]. Occasionally electrostatic electron cyclotron waves are observed. These waves may produce sufficient anomalous resistivity to accelerate particles in the tail region. Huba et al. [1977, 1978b] suggest that the lower-hybrid-drift instability may be the source of these two types of tail electrostatic turbulence.

Coordinated observations between OGO-5 and Vela-4A indicated that PI2 pulsations were generated in the plasma sheet at the onset of magnetospheric substorms [Pytte et al., 1976a]. Both a "neutral charged-particle beam" [Chang and Lanzerotti, 1975] and a garden hose [Kan and Heacock, 1976] instability have been suggested to explain the PI pulsations.

Polar Cusp

Both experimental and theoretical research in this area through 1977 is reviewed by D'Angelo [1977]. Scarf et al. [1975] report an OGO-5 pass on which intense waves and currents were detected at a steep density gradient during a moderate magnetic storm. The wave amplitude may have been sufficient to produce anomalous resistivity which could lead to local acceleration of electrons. Gurnett and Frank [1978] identify four types of noise from Hawkeye-1: ULF/ELF magnetic noise 1 Hz - 300 Hz which can be uniquely associated with the cusp, broadband electrostatic emission which extends up to 100 kHz but peaks in the 10 - 50 Hz range, electrostatic electron cyclotron waves, and whistler mode auroral hiss. The ULF/ELF noise may be caused by a cyclotron resonance, Kelvin-Helmholtz or drift wave instability. Evidence for the Kelvin-Helmholtz instability is given by Kintner and D'Angelo [1977] and by Potemra et al. [1978]. An electrostatic ion cyclotron or ion acoustic current-driven instability is thought to generate the broadband electrostatic noise. The other two noise types have been recognized throughout the auroral region.

Auroral Zone

All predominant types of auroral zone plasma waves--VLF hiss and saucers, electrostatic turbulence and kilometric radiation--seem to be intimately tied in with the auroral particle beams.

VLF Hiss and Saucers

VLF Hiss, also called auroral hiss, occurs in the kHz frequency range and can be observed both on the ground and from satellites. Previous measurements have shown that the waves are propagating downward along auroral field lines from altitudes $\geqslant$ 3000 km. Siren [1975] reports a phenomenon called "fast hisslers" which are bursts of hiss with a whistler mode dispersion. These hisslers seem to originate at altitudes of 1800-30,000 km. Auroral hiss is observed to correlate best with 0.7 keV precipitating electrons as observed with OGO-4 [Laaspere and Hoffman, 1976]. Theories to explain auroral hiss have been developed by Swift and Kan [1975], Maeda [1975], Baker and Weil [1975], and Maggs [1976, 1978] based on the free energy in the auroral electron beam. This beam provides amplification of incoherent whistler mode radiation.

An upward propagating phenomenon called "saucers" seems to have a generation mechanism similar to hiss but at low altitudes due to upward flowing suprathermal electron beams [James, 1976].

Electrostatic Turbulence

Intense electrostatic wave turbulence has been observed in the auroral ionosphere with rockets [Bering et al., 1975] along auroral field lines at ~ 1 R_E altitude [Mozer et al., 1977; Kintner et al., 1978; Hudson et al., 1978; and Temerin, 1978] and out toward the magnetotail [Gurnett and Frank, 1977]. At ~ 1 R_E the noise occurs at ~ 100 Hz with amplitudes up to 50 mV/m and is intepreted as the electrostatic ion cyclotron mode. At higher altitudes, the noise peaks in the 10-50 Hz range with amplitudes of 10 mV/m. A significant feature of this noise is that it is found in regions with large (> 120 mV/m) dc electric fields which may be responsible for the auroral particle accelerations [Mozer et al., 1977]. This noise may produce an anomalous resistivity situation or electrostatic shocks and double layers or both [see discussions by Mozer, 1976; Ionson, 1976; Swift, 1977; Hudson and Mozer, 1978; Shawhan et al., 1978] which can accelerate particles along the magnetic field lines. However, there is not general agreement on the significance of each mechanism. Ungstrup et al. [1977], Whalen et al. [1977], and Ashour-Abdalla and Thorne [1977 and 1978] investigate details of the electrostatic ion cyclotron mechanism for the acceleration and diffusion of energetic ions.

Kilometric Radiation

One of the major accomplishments during this quadrennium was the characterization of kilometric radiation from the earth. This terrestrial kilometric radiation (TKR) or auroral kilometric radiation (AKR) is found to be located on auroral field lines at radial distance of 2-3 R_E predominantly in the local midnight sector at peak emission frequencies of ~ 200 kHz using direction finding techniques from IMP-6 and Hawkeye-1 [Kurth et al., 1975] and lunar occultations with RAE-2 [Kaiser and Alexander, 1976, 1977a; and Alexander and Kaiser, 1976]. From joint observations with IMPs 6 and 8 and with Hawkeye-1, Green et al. [1977] were able to show that the radiation occurs simultaneously within solid angles ranging from 3.5 sr at 178 kHz to 1.1 sr at 56.2 kHz which seems to be controlled by the plasmapause location on the nightside. These measured emission solid angles confirm the estimated angles used by Gurnett [1976b] to derive a peak value of ~ 10^9 watts and an average value of ~ 10^7 watts for the power emitted by the Earth. Kaiser and Alexander [1975], Kennel and Maggs [1976], Gurnett [1976b], and Shawhan [1978] point out the similarity of this emission to that of the Jovian decametric emissions of comparable power but with spectral characteristics scaled by the relative electron cyclotron frequencies. Several theories for kilometric radiation have been advanced [Benson, 1975; Palmadesso et al., 1976; Melrose, 1976; Maggs, 1978 among others]. Polarization observations of kilometric radiation by Gurnett and Green [1978] and by Kaiser et al. [1978] are consistent with it escaping in the extraordinary mode (right hand polarized in the plasma sense); this characteristic is a critical test of the various theories. Because of its intimate association with magnetic disturbances [Voots et al., 1977; Kaiser and Alexander, 1977b] the occurrence and magnitude of AKR may provide a reliable magnetic disturbance index.

Plasmapause and Beyond ($4 < L < 10$)

The plasmapause is distinguished by an order of magnitude drop in the cold electron density in the region of L = 4-8 and the mixing of the hot plasmas associated with the trapped electrons and the ring current ions beyond. These conditions lead to a rich variety of wave-particle interactions in a region that has been reasonably well explored with spacecraft. The predominant plasma wave types undergoing active research include magnetic pulsations and MHD waves, ion cyclotron waves, chorus, and electrostatic electron cyclotron noise.

MHD Waves and Magnetic Pulsations

Vigorous observational and theoretical research has been carried out on magneto-hydrodynamic waves, geomagnetic pulsations, and ULF emissions covering the frequency range of 10^{-3} to 10^1 Hz due primarily to the presence of suitable instrumentation on ATS-1, ATS-6, OGO-5, S^3, and ground magnetometer stations [e.g. Orr, 1975; Taylor et al., 1975a; Kivelson, 1976; Lanzerotti, 1976; Coleman and McPherron, 1976; Kokubun et al., 1976; Lanzerotti et al., 1976b; Raspopov and Lanzerotti, 1976; Wertz and Campbell, 1976; Heacock and Hunsucker, 1977; see also McPherron, 1979].

Pc 5 magnetic pulsations with frequencies of ~ 10 Hz occur at times of maximum ring current development, just after magnetic substorm onset [Barfield and McPherron, 1978]. Correlation of multiple spacecraft with ground magnetometer data lead to the conclusion that Pc 3, 4 magnetic pulsations (10-100 MHz) are a standing wave due to a local field line resonance possibly excited by a surface wave generated at the magnetopause [e.g. Lanzerotti and Fukumishi, 1975; Arthur et al., 1977; Cummings et al., 1978]; the generating instability may be a Kelvin-Helmholtz mechanism [Hughes et al., 1978]. Correlation of Pc 3,4 amplitude with the interplanetary magnetic field direction indicates a possible correlation with the radial magnetic field component [Webb and Orr, 1976; Greenstadt and Olson, 1977; Arthur and McPherron, 1977b]. PI magnetic pulsations are broadband (0.005-0.5 Hz) but irregular emissions associated with the magnetic storms. The polarization characteristics are found to vary significantly from station-to-station and at S^3 [Fukunishi, 1975a; Lin and Cahill, 1975] and the amplitude measured on the ground is less by an order of magnitude [Heacock, 1977]. Some ground events apparently originate in the ionosphere due to particle precipitation [Heacock and Hunsucker, 1977].

Evidence is mounting that the substorm related IPDP (intervals of pulsations of diminishing period ~ 0.1 Hz) events are due to the proton cyclotron instability from 1-100 keV protons drifting westward in the vicinity of the plasmapause [Heacock et al., 1976; Bossen et al., 1976a; Horita et al., 1978]. Pc 1 magnetic pulsations are persistent emissions in the 0.1-10 Hz range lasting for hours. Bossen et al. [1976b] find, for example, that the Pc 1 characteristics are consistent with a source region at the plasmapause due to a cyclotron resonance of ~ 30 keV protons in a 30 cm^{-3} density region [see also Taylor et al., 1975b; Lewis et al., 1977].

Ion Cyclotron Waves

It has long been thought that ring current ions (~ 30 keV) at the plasmapause can lead to the growth of ion cyclotron waves which can lead to the decay of the ring current itself, to inward diffusion of energetic electrons, and perhaps to SAR arcs. Many authors have proposed more detailed theories including Wandzura and Coroniti [1975], Davidson [1975], Murphy et al. [1975], Cornwall [1975], Joselyn and Lyons [1976], Southwood [1976], Lin and Parks [1976], and Lanzerotti et al. [1978a]. However, Taylor and Lyons [1976] found only 18 large amplitude (0.4-6 gamma) ion cyclotron wave events in the frequency range of 1-30 Hz with S^3. Some of these events were associated with enhanced ion fluxes. Other events were not associated with changes in the ion distribution. A similar search using Hawkeye-1 turned up only five events in an 18 month period. All events occurred during the recovery phase of a magnetic storm near the plasmapause [Kintner and Gurnett, 1977]. Lyons [1976] suggests that the observations of waves and ions are inconsistent with the theory and that the low energy ring current ions may not be protons.

Chorus and Hiss

In the vicinity of the plasmapause VLF chorus and hiss emissions in the kHz range have been observed near the equator for $4 < L < 10$ in association with ~ 10 keV electrons at time of magnetic storms [e.g. Burtis and Helliwell, 1975, 1976; Taylor and Anderson, 1977; Anderson and Maeda, 1977; Imhof et al., 1977; Chan and Holtzer, 1976]. In addition Tsurutani and Smith [1977] report a second type of high latitude chorus which is not substorm dependent. Theoretical work continues on the concept that chorus is generated by a cyclotron feedback mechanism with the keV electrons [Maeda et al., 1976; Burton, 1976; Curtis, 1978; Maeda et al., 1978].

Electrostatic Electron Cyclotron Harmonic Radiation

Further observations of electrostatic noise bands near the electron plasma frequency and near $(n + \frac{1}{2})$ harmonics of the electron gyrofrequency from the plasmapause to 10 R_E at all local times and latitudes explored by IMP-6 are reported by Shaw and Gurnett [1975]. This 1975-78 period has been marked, principally, by an intense effort to understand this phenomenon theoretically. The models have evolved from the work of Ashour-Abdalla and Kennel [1975] through that of Gaffey and LaQuey [1976] and Maeda [1976] to the present understanding of Ashour-Abdalla and Kennel [1978a] and of Hubbard and Birmingham [1978]. Both groups agree that the noise band can be generated by a loss cone instability resulting from the mixture of cold electrons (< 100 eV) and hot loss cone electrons (~ 1 keV) in the region outside the plasmapause. The required instability can occur if the cold upper-hybrid frequency exceeds the wave frequency. Initially the instability may be non-convective in which electrons are rapidly heated until it becomes convective. Conditions for the instability are most easily met for the 3/2 harmonic; other harmonics are likely depending on the cold to hot electron density ratio. Understanding of this noise phenomenon is particularly important because this electrostatic turbulence may lead to precipitation of 1-10 keV electrons.

Plasmasphere and Ionosphere

Within the plasmasphere the plasma waves are predominantly whistler mode generated or amplified by energetic electron bunches or emitted into the plasmasphere from lightning and man-made sources. In the ionosphere with significant density, temperature and compositional gradients, a number of turbulence phenomena can develop.

Plasmaspheric Hiss

Plasmaspheric hiss, in the frequency range of 100-1000 Hz, is found throughout the plasmasphere particularly during periods of magnetic activity [Tsurutani et al., 1975; Parady et al., 1975; Thorne et al., 1977]. The recent observations seem to be consistent with the electron cyclotron resonant generation mechanism due to > 30 keV electrons trapped in or injected into the plasmasphere [Thorne and Barfield, 1976]. Tsurutani et al., [1975] suggest that hiss may be the dominant loss mechanism for trapped electrons by pitch angle scattering.

Whistlers

Lightning generated noise coupled into the plasmasphere results in discrete, falling-tone, plasma waves. These whistler waves are observed throughout the plasmasphere and out to several R_E beyond the plasmapause. Since whistler generation and propagation is well understood, whistler traces are used to deduce electron density profiles and convection electric fields for the plasmapause and plasmasphere. Carpenter [1978a] reviews whistler and VLF noise phenomena just outside the plasmapause. Park et al. [1978] summarize the whistler-deduced electron density variations within the plasmasphere and Ho and Carpenter [1976] and Morgan [1976] deduce the plasmasphere structure, for example. From drifting whistler ducts, convection electric fields near the plasmapause can be estimated as shown, for example, by Park [1976a] and Carpenter [1978b]. Field values up to 0.2 mV/m are found at times of magnetic substorms. In the inner plasmasphere, whistlers are observed with a variety of dispersion characteristics due to refraction processes caused by density and compositional gradients in the ionosphere. Characteristics of magnetospherically reflected [Edgar, 1976] and subprotonospheric [Raghuram, 1975] whistlers have been further investigated.

Power Line Harmonic Radiation

A significant discovery during this quadrennium is that kHz harmonic radiation of the 50 and 60 Hz power grids can couple into the plasmasphere and be amplified by ~ 30 dB to amplitude levels which may cause energetic electron precipitation [Helliwell et al., 1975; review by Park, 1976b]. Evidence is presented that the power line harmonic radiation can produce increased chorus activity [Luette et al., 1977] and whistler precursors [Park and Helliwell, 1977a]. The possibility of man-made emissions having a significant effect on the trapped electrons has evoked much discussion; Lyons and Williams [1978] argue that local effects might occur but other more dominant processes control the overall structure of the radiation belts.

Controlled Wave Generation Experiments

Extensive use is being made of VLF transmitters to inject known wave patterns into the plasmasphere in order to induce wave-particle interactions. Injected waves arrive at the equatorial interaction region and organize the energetic electrons to coherently emit waves of a similar frequency with 20-40 dB higher amplitudes [Stiles and Helliwell, 1975, 1977; Koons et al., 1976; Raghuram et al., 1977; Inan et al., 1977; Dunckel and Helliwell, 1977; Dowden et al., 1978]. Transmitter experiments have been carried out to understand natural wave-particle processes such as whistler duct motions [Carpenter and Miller, 1976], simulation of power line harmonic radiation [Koons et al., 1978; Park and Chang, 1978], stimulation of magnetic pulsations [Fraser-Smith and Cole, 1975; Willis and Davis, 1976; Koons, 1977; Newman, 1977], and particle precipitation [Koons, 1975; Bell, 1976; Inan et al., 1978].

Waves generated in the ionosphere by rocket borne electron accelerators have been reported by Monson et al. [1976], Kellogg et al. [1976], and Monson and Kellogg [1978]. Whistler mode waves and emissions near the plasma frequency and at harmonics of the electron gyrofrequency are radiated. Laboratory experiments by Bernstein et al. [1975, 1978] in electron beam-discharge plasmas exhibit wave emissions similar to the rocket experiments. Whether these mechanisms may be the source of kilometric radiation is still being assessed [Monson and Kellogg, 1978]. Laboratory experiments yielding whistler filamentation and VLF hiss have been conducted by Stenzel [1976, 1977]. Work is proceeding on the properties of antennas and probes in plasma which may be important for the emission and diagnostics of waves injected from Spacelab [Stenzel et al., 1975; Harker, 1975; Kelley et al., 1976b; DeWitt et al., 1976; Stenzel, 1976; Christensen et al., 1977].

Ionosphere

Many plasmasphere and auroral zone plasma-wave phenomena already discussed are observable at ionospheric altitudes. Properties of the ionosphere and atmosphere can affect the wave properties of magnetic pulsations as seen on the ground [Hughes and Southwood, 1976; Lanzerotti et al., 1978b]. Kelley et al. [1975] report on ELF observations from OV1-17 and OGO-6. Some phenomena such as irregularities causing spread-F are unique to the ionosphere and are brought about by density, temperature, and compositional gradients. Radar spread-F is a result of radar waves being backscattered from density irregularities in the F-region of the ionosphere. Coordinated ground radar and rocket in situ observations are reported by Kelley et al. [1976a] and by Morse et al. [1977]. Several theoretical treatments of the problem including Hudson and Kennel [1975], Kelley and Ott [1978], Huba et al. [1978a], and Costa and Kelley [1978b] suggest that the Rayleigh-Taylor instability is initiated by steep density gradients in the lower ionosphere. These large spatial wavelengths produce density gradients which allow growth of drift waves with characteristic wavelengths below the ion gyroradius. The large scale structures are the F-region "bubbles"; the radar backscatter is caused by the drift waves. In the auroral region incoherent backscatter radar is used to study ionospheric electric fields, conductivities, and currents [e.g. Doupnik et al., 1977]. The Buneman-Farley two-stream instability may produce turbulence leading to some of the echoes [Wang and Tsunoda, 1975], for example. Sufficient radar power input will cause heating of the plasma which drives plasma-wave instabilities. It is thought that electrons are accelerated by Langmuir waves excited by a parametric instability. In the Platteville experiments red line and green line airglow in enhanced [Weinstock, 1975].

Jupiter and Other Planets

Both escaping and non-escaping plasma waves should be generated by various wave-particle processes in the magnetospheres of Jupiter, Saturn and Uranus and within the ionopauses of the other planets.

Escaping Plasma Waves

Radio emissions from Earth, Jupiter, Saturn and Uranus in the 100 kHz - 40 MHz frequency range have been observed. It is thought that the mechanisms which produce these escaping plasma waves at frequencies related to the electron gyrofrequency may be similar [Kaiser and Alexander, 1975; Kennel and Maggs, 1976; Brown, 1976; Gurnett, 1976b; Shawhan, 1978]. Recent ground-based and satellite observations of the Jovian decametric and hectometric observations are reviewed by Carr and Desch [1975]. Further research has concentrated on motions of the Io-related sources [Thieman et al., 1975], directivity and stimulation of emissions [Boyzan and Douglas, 1976], modulation below 8 MHz [Desch and Carr, 1978] and morphological characteristics over a 19 year period [Thieman and Smith, 1978]. Mechanisms for the decametric radiation have been reviewed by Smith [1975]. In recent work Shawhan et al. [1975], Shawhan [1976] and Smith and Goertz [1978] develop the idea that electrons are accelerated along the Io flux tube due to the potential developed across Io as the Jovian magnetosphere rotates. Theories for converting the $< 10^{13}$ watts of electron beam energy to escaping plasma waves continue to be developed [e.g. Benson, 1975; Melrose, 1976; Ratner, 1976].

Trapped Plasma Waves

The Voyager-1 and 2 spacecraft will carry wave instrumentation [Scarf and Gurnett, 1977; Warwick et al., 1977] through the Jovian magnetosphere in 1979 to provide the first direct measurements of trapped plasma wave phenomena. Using analogies with the terrestrial magnetosphere processes, Scarf [1975b] makes predictions. Melander and Liemohn [1976] have constructed a CMA diagram for wave modes in the Jovian magnetosphere. From analysis of the Pioneer-10 and 11 energetic electron data it has been possible to indirectly deduce the characteristics of whistler mode turbulence which may drive the pitch angle diffusion process which accounts for the loss of energetic particles. This noise should be found in the range for $L = 3 - 10\ R_J$ and at frequencies of 0.2 - 2 kHz with amplitudes comparable to that for ELF hiss or chorus at the Earth [Coroniti, 1975; Scarf and Sanders, 1976; Barbosa and Coroniti, 1976; Thomsen et al., 1977; Sentman and Goertz, 1978]. Eviatar et al. [1976] predict that ion cyclotron turbulence near the sodium gyrofrequency will occur due to the sodium plasma injected by Io.

Research Emphasis for the Next Quadrennium

During the next quadrennial period at least three sets of satellites will be making comprehensive wave, particle, plasma, and field measurements throughout the magnetosphere. The Mother-Daughter pair ISEE-1 and -2 are exploring the bow shock, magnetopause, magnetosheath, near magnetotail, plasma sheet, and plasmasphere with the capability to resolve spatial from temporal variations while ISEE-3 monitors the solar wind. An example of a spectrogram from the ISEE-1 sweep frequency receiver is shown in Figure 2; VLF transmissions, electron plasma frequency noise, electrostatic electron cyclotron emission, and plasmaspheric hiss are clearly evident as ISEE-1 crosses the plasmapause. Simultaneously, GEOS-1 and -2 are making comprehensive measurements in the region of 6 R_E which is ideal for observing plasmapause phenomena. In 1981 Dynamics Explorer-A and -B are to be launched into polar orbits. DE-A orbit is elliptical with apogee near 4 R_E and DE-B orbit is nearly circular at low altitude so that auroral and plasmapause phenomena can be simultaneously studied at several points along a magnetic field line. Also during this time period the Pioneer-Venus plasma wave measurements will be analyzed as will those of Voyager-1 and -2 to give the first direct assessment of trapped plasma waves at other planets.

Active wave stimulation experiments should continue during this period utilizing VLF transmitters, particle accelerators, and chemical releases in the magnetospheric plasma as well as in laboratory plasma chambers and computer simulations. In 1980 and 1981 electron beams are to be injected from the Space Shuttle (OSS-1 and Spacelab-1) into the ionospheric plasma and the consequences, including plasma wave emission, diagnosed. From a subsatellite of Spacelab-2 in 1982 the characteristics of the Orbiter wake and the effects of large propellant releases are to be investigated.

From the body of current observational data and that expected from currently operating spacecraft, from the outcome of active experiments which concentrate on specific processes, and from the treatment of these results in terms of sound plasma theory it should be possible to make substantial progress on the following problems during 1979-1982:

-- the identification of specific wave phenomena and the role they play in the formation of the bow shock and in processes in the magnetosheath.

-- the importance of the electrostatic ion cyclotron turbulence in the auroral zone and its relationship to electrostatic shocks and to the generation of VLF emissions and kilometric radiation.

-- the adaptation of kilometric radiation theories to the numerous observational details and the assessment of this resulting mechanism for explanation of apparently similar emissions from Jupiter, Saturn, and Uranus.

-- the further categorization of MHD waves and magnetic pulsations and the correlation of characteristics with the state of

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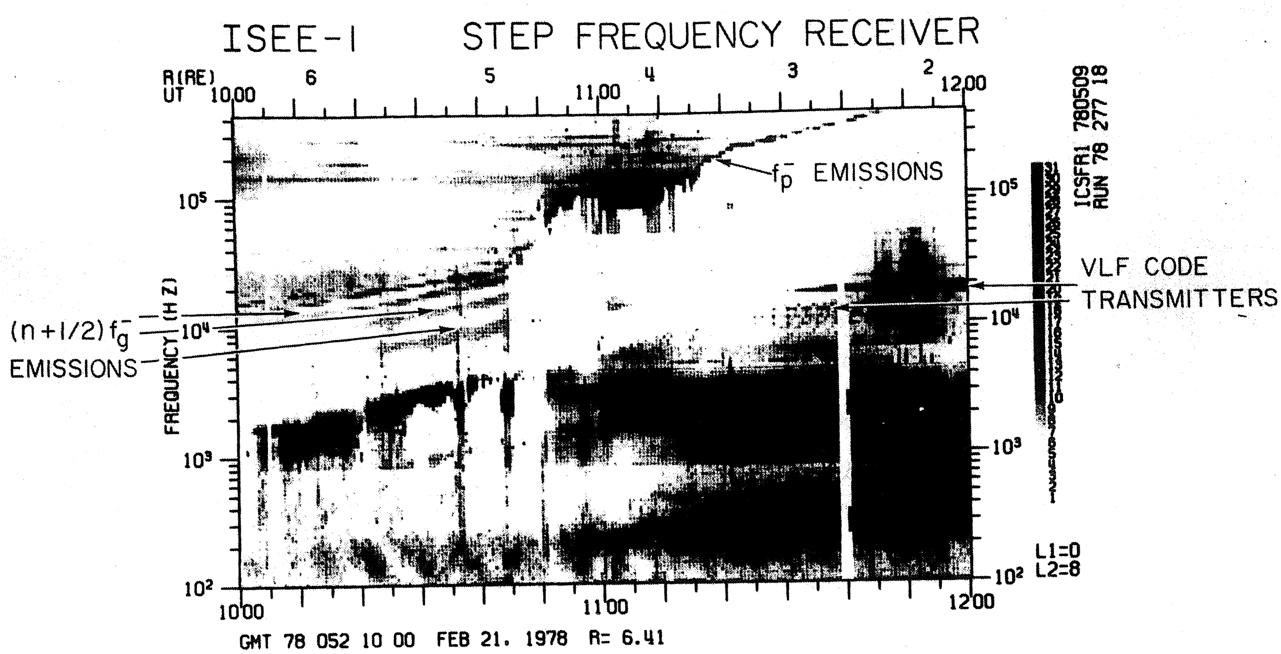

Figure 2. Spectrogram of magnetospheric plasma waves in the vicinity of the plasmapause from ISEE-1. VLF code transmissions, electron plasma frequency (f_g^-) emissions, electrostatic electron cyclotron emissions (at $(n+\frac{1}{2})\ f_g^-$) and plasmaspheric hiss (below $\sim 10^4$ Hz) are clearly evident.

the solar wind and magnetosphere to better determine generation mechanisms and wave characteristics.

-- the judgment of whether ion cyclotron waves have a significant effect on the lifetimes of ring current ions.

-- the details of the whistler mode waves--energetic electron interaction mechanism resulting in the generation of hiss, chorus and discrete emissions and in the precipitation of energetic electrons including development of the evidence for enhanced precipitation due to man-made power line harmonic radiation.

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